LESSONS LEARNED FROM THE USE OF A GPS RECEIVER IN LESS THAN OPTIMAL CONDITIONS

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ABSTRACT *– The French space agency, CNES, has long been involved in Earth observation satellites, and in the development of tracking systems to support them. For example, the DORIS high precision one-way Doppler tracking system was conceived and implemented for the French-American TOPEX/Poseidon mission. It led to the development of the DIODE series of real-time on-board orbit determination software. In parallel, CNES managed the development of the ALCATEL space GPS receivers TOPSTAR 300 and 3000, and created for them the DIOGENE real-time orbit determination software. The first flight of DIOGENE is now successfully taking place on the HETE-2 spacecraft. However, the equatorial orbit at about 650 km altitude combined with a Sun pointed attitude leads to relatively unfavorable GPS visibilities, and a high level of ionosphere perturbations. In addition, for power limitation reasons, the receiver can only operate a few orbits per day around the sub-solar point, except around full moon when the main payload is off. Soon after launch it became clear that all these factors biased the point solution, perturbed the on-board real-time orbit, and made ground processing challenging. It was also noticed that the on-board clock is drifting at a very high rate, with resets at the beginning of each session, and that the standard GPS processing that was used and validated on TOPEX had to be modified for the processing of the HETE-2 data.This paper presents the various difficulties that were encountered and how they were dealt with. The emphasis is placed on how the ionosphere problem was resolved in this case to obtain a ground-corrected data set and a reference orbit, and how well the GPS receiver and DIOGENE perform.*

KEYWORDS: GPS, orbit determination, real-time on-board orbit determination, ionosphere correction.

INTRODUCTION

The original intent of the Global Positioning System (GPS) was to enable direct positioning of anything, from fixed reference stations to mobiles, including aircraft, with a precision ranging from decimeters to tens of meters. The potential of these techniques for satellite positioning was obvious, but also clearly technically challenging. The high velocity of orbiting spacecraft causes large Doppler shifts and severely limits the duration of passes, leading to difficulties in signal processing. In addition the harsh radiation environment is hardly compatible with the heavy computational requirement of GPS signal processing.

CNES realized more than 10 years ago the importance of GPS for satellite positioning, and commissioned SEXTANT Avionique to develop a space based receiver from its aviation line of products. In 1992, NASA, CNES and the Massachusetts Institute of Technology (MIT) agreed to use a CNES supplied GPS receiver on-board the HETE spacecraft to achieve precise time-tagging of gamma ray bursts [1]. The first TOPSTAR 300 GPS receiver was delivered by CNES to MIT in December 1993. The launch occurred in November 1996, and, unfortunately, failed. It was then decided to fly a recurrent HETE-2 spacecraft using spares of the instruments. The delay was used on the CNES side to add the newly developed DIOGENE (**D**etermination **I**mmediate d'**O**rbite par **G**PS **E**t **N**avigateur **E**mbarqué : immediate orbit determination with GPS and on-board navigator) real time orbital navigation software to the receiver, in addition to the standard point positioning solution (Least Squares Instantaneous Resolution, LSIR). In the mean time, the signal processing functions were validated with the TOPSTAR 100 receiver which operated successfully on the Atmospheric Reentry Demonstrator which was launched in 1998 by Ariane V [2].

The TOPSTAR 300 receiver of HETE-2 has 8 L1-C/A channels and is equipped with an antilatchup device. Its physical characteristics are 1 kg and 0,8 liter. The GPS antenna is a low cost space qualified L1 patch provided by RAYAN (Dourdan, France). This 9.6 cm diameter antenna was designed to minimize the antenna pattern distortions due to the spacecraft structure (the face where the GPS antenna is mounted is particularly full, with in particular two solar sensors very close to each side of the patch).

The TOPSTAR 300 GPS receiver is equipped with two orbital navigators. The LSIR computes the position, velocity and time solution whenever 4 GPS satellites are tracked, while DIOGENE uses a dynamical model of the motion and a Kalman filter to produce a solution at all times.

The receiver can operate in two modes, the operational mode (7 watts power consumption) and the stand-by mode (0.5 watts). The navigation filters only work in operational mode. At every transition to stand-by mode, the last state vector (position, velocity, clock and clock drift) is memorized as well as the more recent GPS ephemeris. When the receiver switches back to operational mode, DIOGENE quickly extrapolates the stored state vector, to provides pseudovelocity estimates to the receiver. With this help the GPS satellites in view can be reacquired in about 2 minutes.

OPERATIONAL CONDITIONS

HETE-2 (High Energy Transient Experiment) is a collaborative program between NASA and the Center for Space Research of the MIT dedicated to the observation of Gamma and X-ray bursts, and exploring the correlation between these events. The HETE-2 microsatellite (about 110 kg) was placed into a nearly circular ($e \approx 0.001$) and equatorial orbit ($i \approx 2°$) by a Pegasus Rocket in early October 2000. The altitude of the orbit was around 650 km at launch, and decreases at the rate of about 1 km per month because of drag (HETE-2 does not have any orbit control capability).

The HETE2 spacecraft is 3-axis stabilized. Its main instruments are anti-Sun pointed, to observe the Sky, preferably when the satellite is eclipsed by the Earth. The GPS antenna is mounted on the opposite face and is always turned toward the Sun. This peculiar geometry leads to a complete interruption of tracking when the satellite is in the Earth shadow. This is optimal in terms of power consumption: on each orbit the receiver works in operational mode around the sub-solar point, then switches to a stand-by mode for the rest of the orbit, when the main payload is active.

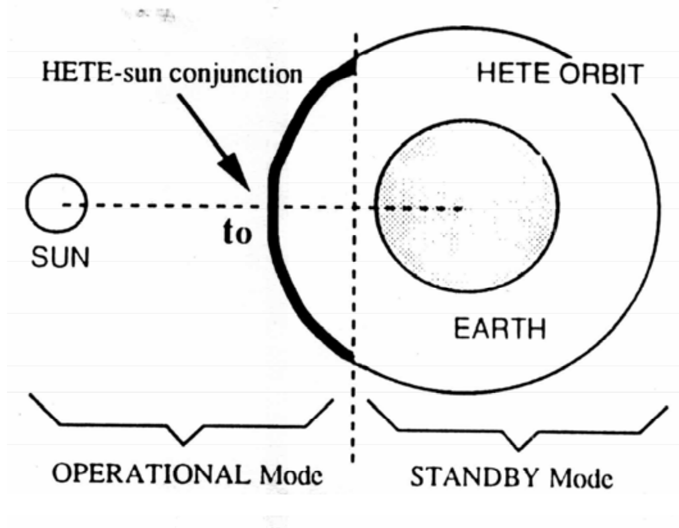


Fig. 1 - Mode cycling along an HETE-2 orbit

This operational configuration is not well suited for orbit determination. In order to be able to evaluate the performance of the receiver and of DIOGENE it was thus agreed with the MIT to operate from time to time in an "orbit determination" mode with nearly continuous operation. However, there is also a limitation coming from the capacity of the telemetry to download all of the tracking data. As a consequence, the first "orbit determination" session in February 2001 was corrupted by the fact that the downloading of the data was not in phase with the optimum acquisition period, leading to a very unfavorable geometry. And it was only in July 2001 that 5 days of data could be acquired for orbit determination purposes. But even then, the data gaps are very large as can be seen on figure 2 where points are plotted in a true anomaly versus time diagram whenever there is at least one measurements available for a one day period (day 184, 2001).

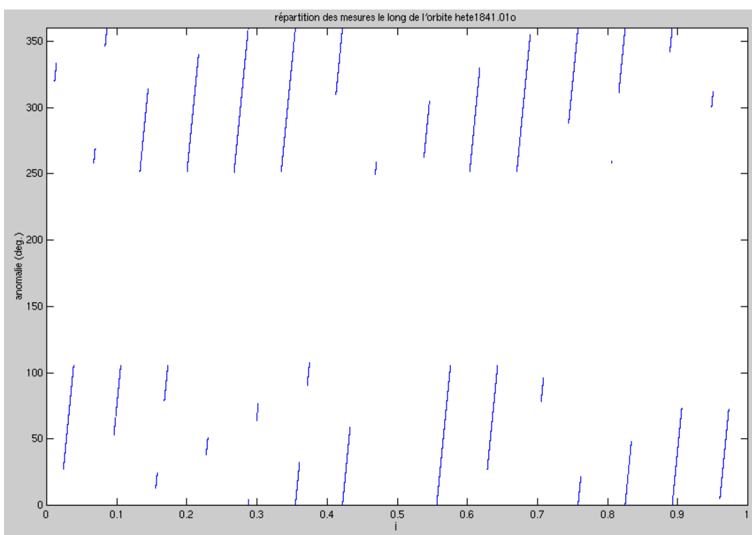
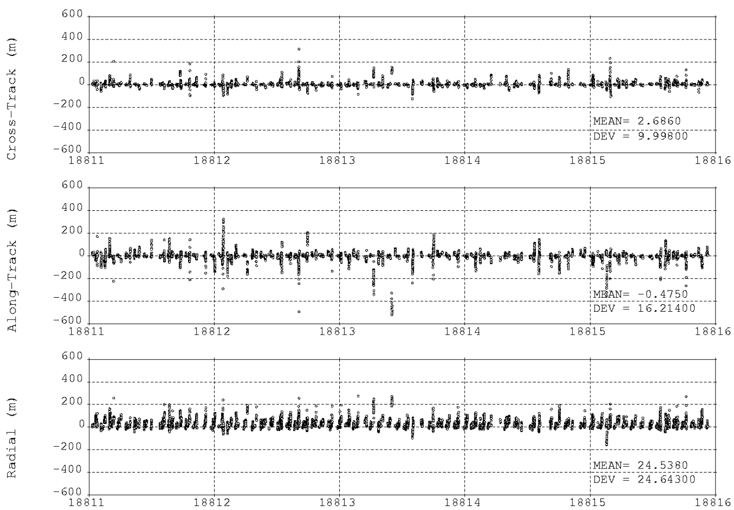


Fig. 2 – GPS visibilities during one day

Later on, it was noted that the main payload couldn't operate properly during full Moon periods. As a consequence, a few days of increased GPS tracking can be scheduled at each full Moon. But, all in all, this does not offer a very good coverage of the orbit. And, in addition, continuous data arcs are short, thus limiting the ability to evaluate orbit precision through the use of overlapping arcs.

But the worst problem comes from the geometry itself. At the sub-solar point the GPS antenna is pointing upward toward the GPS constellation, and its field of view is half the sky. However, starting at 25 degrees from that position on either side, the field of view of the antenna starts to be blocked by the Earth, until it is completely reduced to zero when the angle reaches 155 degrees. In addition, many of the GPS satellites are seen through the ionosphere, with this proportion increasing as the satellite moves away from the sub-solar point.

As the ionosphere presents a high Total Electron Count (TEC) at equatorial regions, its influence on the TOPSTAR single frequency data is very important. In addition, the effect of the ionosphere is "geometrically" correlated with the increase in the GDOP due to the reduced field of view as the spacecraft moves away from the sub-solar point. This leads to a very degraded point positioning solution as can be seen from Figure 3 (the technique used to compute the reference solution will be presented below).



	mean	std. dev.
Radial (m)	24.5	24.6
Along-track (m)	-0.5	16.2
Cross-track (m)	2.7	10.0

Fig. 3 – performance of the on-board point positioning solution

The positive radial bias is easily explained by the influence of the ionosphere: the path to the GPS satellites seen below the local horizontal plane is lengthened by the ionosphere, while those above this plane are less affected. This tends to shift the position solution upward, that is in excess in the radial direction.

HANDLING THE IONOSPHERE

Given the tracking geometry, no proper reference orbit can be obtained without first correcting the data for ionosphere delays. For single frequency receivers, this is usually performed through the use of the Differenced Range Versus Integrated Doppler (DRVID) technique. Because the ionosphere is a simple dispersive medium the group velocity (the one at which the code travels) and the phase velocity (the one at which the phase travels) are related by $v_g v_p = c^2$ so that the delay induced by the crossing of the ionosphere in the propagation of the code is equal to the advance in the propagation of the phase:

$$p_1 = p + e \quad \text{and} \quad \lambda_1 \left(L_1 + N_1 \right) = p - e$$

with p_1 the pseudo-range measurement (in meters), $\lambda_1 L_1$ the carrier phase measurement converted in meters using the wavelength λ_1, N_1 the ambiguity of the carrier phase measurement (cycles), p the pseudo-range without ionosphere delay (including clock and geometrical errors among others) and e the ionosphere delay (in meters).

The ambiguity can be eliminated by computing the time difference of the above equations between the measurement dates t and $t-\delta t$, leading to the increase in ionosphere delay during δt

$$\delta e = \frac{1}{2}\left(p_1(t) - p_1(t-\delta t) - \lambda_1 D_1(t)\right)$$

with $D_1(t)$ the integrated Doppler measurement in cycles.

In the case of the HETE-2 this processing cannot be applied directly, as the receiver only provides the pseudo-range at a rate constrained by the telemetry (every 2 or 5 seconds in the samples processed for this paper) and the Doppler integrated over the last second before the date for which the pseudo-range is provided.

To use the DRVID, the variation in pseudo-range over the last second (synchronous with the integrated Doppler measurement) was computed using a polynomial fit to the pseudo-range measurements over an interval surrounding the date of interest. Subsets of about 12 pseudo-ranges were typically used to smooth the pseudo-range and compute the one second difference just before the middle of the sample. This was then used to compute the ionosphere delay increment over this second, which was then linearly transformed into an increase over the sampling rate of the pseudo-range. These estimates were then integrated over a pass to reconstruct the ionosphere delay up to a constant.

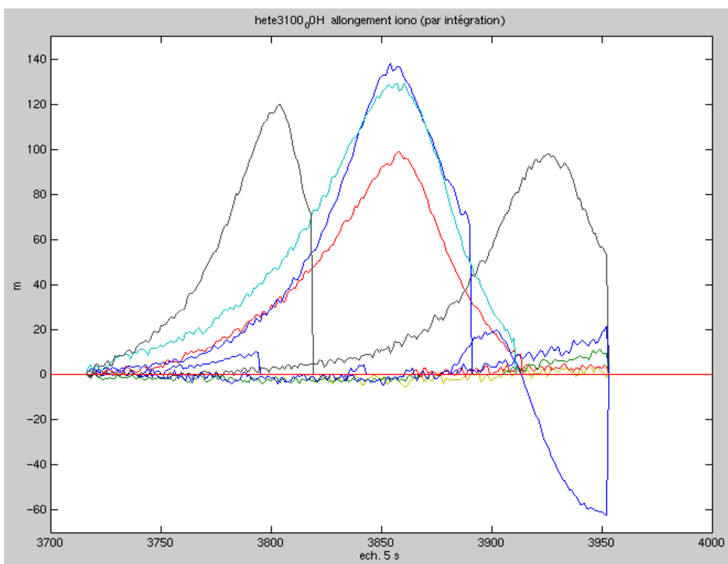


Fig. 4 - Typical ionosphere delays measured on board HETE-2

Figure 4 shows the ionosphere delays obtained for a few passes of day 310, 2000 as a function of time. Delays have been set to 0 at the beginning of each pass to remove the unknown bias. This clearly demonstrates that the ionosphere delays can often be greater than 100 meters. The precision on these estimates is given primarily by the noise of the reconstructed differenced range, as the noise on the Doppler is very small. For a noise level of 5 cm per 5 seconds, which results from an analysis of the smoothing offered by the polynomial for a 2.5 m rms pseudo-range noise, this leads to about a 10 meter random walk like error over the pass.

A better understanding of the characteristics of this ionosphere delay can be obtained by plotting the delay as a function of the angle of the line of sight of the GPS satellites over the local horizon (defined as the plane perpendicular to the radial vector). The bias in the delays can then be set to zero for high elevation angles. Figure 5 shows the cumulated result for all the passes from day 302, 2000 which contained measurements collected at an elevation angle above 45 degrees.

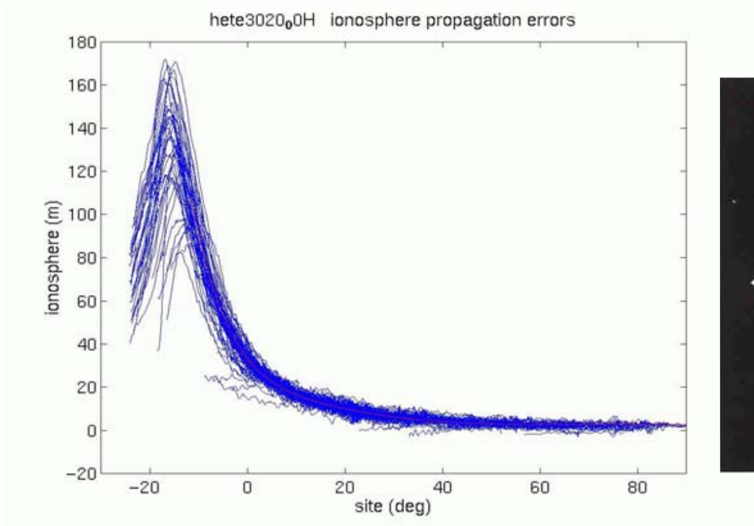
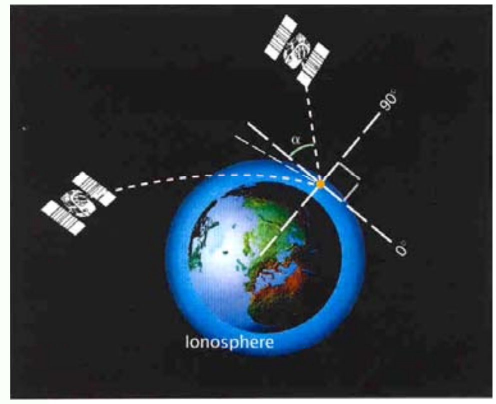


Fig. 5 - Ionosphere delays versus the elevation angle



Definition of the angles
α = elevation

Figure 5 clearly shows that the ionosphere delay increases when the elevation goes from 90 degrees down to about -15 degrees, and then decreases until it reaches the Earth mask at about -25 degrees. The observed maximum at -15 degrees corresponds to rays that graze the F2 ionosphere layer at an altitude of about 350 km. For angles below –15 degrees, the line of sight crosses the ionosphere twice, but the integrated effect is smaller than when it lies within the main ionosphere layer.

These results prove that part of the ionosphere delay can be empirically corrected. Below -10 degrees the dispersion between passes is very large, while above that limit all the passes look very much alike. Thus the ionosphere delay per pass can be approximated above –10 degrees by a common function of the elevation angle plus a pass dependant bias.

$$e_i(\alpha) \cong P_4\left[(1-\cos\alpha)^2\right] + C_i \quad \text{for } \alpha \geq -10°$$

where P4 is a degree 4 polynomial adjusted by least squares over all the passes of the day which contain measurements above –10 degrees. This procedure determines the values of the C_i for all those passes. The value of the ionosphere used to correct the pseudo-ranges is then $e_i(\alpha) - C_i$. There remains an unknown global bias, which corresponds to the ionosphere vertical delay, common to all the GPS in view at the time. As this bias is global, it goes into the clock solution and does not impact the orbit.

Figure 6 shows the residuals of the point positioning solution, without and with these corrections, for the same initial measurements. The RMS of the residuals is 14.2 m before correction, and is reduced to 2.6 m after correction. This latter value is very close to the estimate of the pseudo-range noise that can be derived from a spectral analysis of the orbit determination residuals after removal of all long period variations (typically the ionosphere over a pass) and of the clock. This demonstrates the good quality of the ionosphere correction.

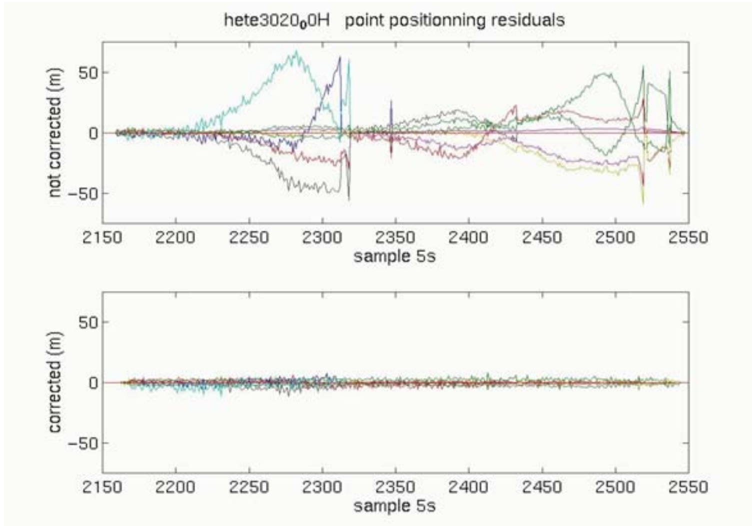


Fig. 6 - Residuals of the point positioning solution before and after ionosphere correction

COMPUTATION OF THE REFERENCE ORBIT

Precise orbit determination software such as ZOOM, the CNES software used for the production of TOPEX/Poseidon's precise orbits, are designed to process GPS pseudo-range and phase data. In this respect, the processing of the HETE-2 data is unusual. Ionosphere corrected pseudo-ranges are not really pseudo-range like measurements, as they contain an ambiguity coming from the ionosphere bias per pass, and they are not phase like because of the high noise level. In addition, there is only one data type. Usually, the noisy pseudo-range is used in the solution to stabilize the very precise, but ambiguous, phase data: ambiguities are then obtained by using both the coherence of the data with a global orbital solution and a global adjustment to the pseudo-ranges.

In the case of HETE-2, the only available data are ambiguous, and a stabilization mechanism is needed. The ideal approach would be to constrain the unresolved ionosphere bias, to a low level corresponding to the estimated value of the vertical content of the ionosphere above 650 km. In practice, a simpler solution was implemented, using the same measurement to compute and stabilize the solution. The ionosphere corrected pseudo-ranges are treated both as accurate (with 2.5 m noise level) ambiguous measurements (phase-like) and as low accuracy (with 250 m noise level) absolute measurements (pseudo-range-like). In this way the ambiguities are constrained to remain close to zero.

The HETE-2 data are also difficult to process in another way. The clock of the on-board receiver is freely drifting so that the on-board and GPS time scales can be very far from each other. This has two consequences. First, pseudo-ranges can reach very large values incompatible with the RINEX format. Second, and most important, the orbit determination process has to iterate many times because of the non-linearity of the problem with respect to this clock parameter: at the first iteration, the clock offset translates into a false measurement ambiguity, which perturbs the solution until ambiguities and clock both reach their final values.

A similar problem exists with TOPEX. To generate the export data sets, the Jet Propulsion Laboratory interpolates the 1-second phase data to recreate both pseudo-range and phase data synchronous with the GPS time scale [3]. For HETE-2 this process cannot be used as only pseudo-ranges and 1 second Doppler are available[1]. Instead a procedure to speed up convergence was implemented at preprocessing: the

[1] The data interpolation can only be done if pseudo-ranges are available at the 1 s rate during orbit determination sessions. This is now the case, but this was not yet true when the analysis for this paper was conducted.

reception time of the signal and the values of the pseudo-ranges are simultaneously modified to reduce the magnitude of the clock correction. This requires the computation of a rough estimate of the clock correction using a point position solution after each interruption in the data.

The parameterization used to compute the orbit afterwards is fairly standard. The dynamical model involves the TOPEX standards (JGM-3 gravity field, FES 95.2 ocean tides, Wahr solid Earth tides, third body perturbations, DTM atmosphere density, Knocke-Ries albedo …) for simplicity reasons. In addition to the usual state vector the empirical parameterization includes an 8 hr drag factor, and daily once per revolution terms along-track and cross-track. The satellite model is a constant area model for solar radiation (Sun pointed) and a box for drag. The on-board clock is modeled as a stochastic white noise at the data rate. Pass biases are also adjusted to account for the remaining ionosphere bias. No stochastic forces were used because of the high data noise.

If no pass biases are adjusted the RMS of the residuals is around 3.6 m. This value is high compared with the expected 2.5 m noise level of the pseudo-ranges themselves. However, when pass biases are estimated, the RMS of the residuals reduces to 2.7 m, while the RMS of the un-biased pseudo-ranges which are used to stabilize the solution raises to 4.6 m. This is consistent with a 2.5 m pseudo-range noise and about the same level of residual ionosphere error in the "ionosphere corrected" data.

The precision of the resulting orbit can only be assessed by computing the statistics of overlap comparisons between adjacent but independent arcs. Considering the limited size of the available data set, this technique can only be used over two or three arcs. The RMS of the overlaps are at the few meters level, but work is under way to analyze more precisely the nature of the orbit error, and in particular to estimate how the orbit error increases between the sub-solar point which is well observed to the anti-solar point where no data is ever available.

DIOGENE

The DIOGENE real-time orbit determination software [4] is a Kalman filter developed in-house at CNES on the basis of the experience acquired with DIODE [5]. It processes pseudo-range and integrated Doppler measurements at a 30 s rate, and includes both sophisticated dynamical models (gravity field JGM-3 up to degree and order 40, Sun and Moon third body perturbations and associated solid earth tides, box and wing model for solar radiation pressure, thrusts, …) and parameterization (initial conditions, clock bias and drift, radiation pressure coefficient, thrust, …).

Not all of these features are implemented in the HETE-2 prototype version. Initially DIOGENE was not supposed to fly on the TOPSTAR 300 receiver, but only on the 3000 version. The opportunity to fly DIOGENE on HETE-2 lead to a special effort to include a prototype version of DIOGENE in the receiver. It replaced a simple orbit propagation model designed to help restart the receiver after stand-by periods. In the TOPSTAR 3000 version, DIOGENE is even better integrated with the receiver, for example by helping preposition the tracking loops to improve signal acquisition.

The main error sources for DIOGENE real-time orbit determination are the ionosphere, which is not accounted for in the models, the use of broadcast ephemerides and clocks for the GPS satellites, and the lack of knowledge of the attitude of the spacecraft. The ionosphere related error far outweighs all the other contributions.

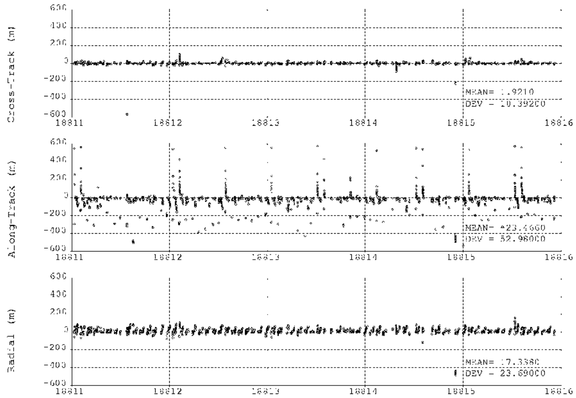


Fig. 7a – DIOGENE flight results

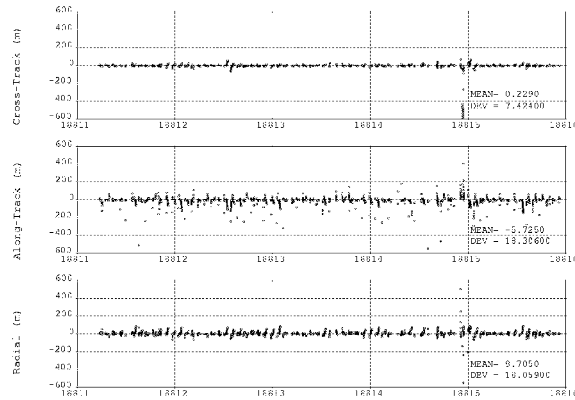
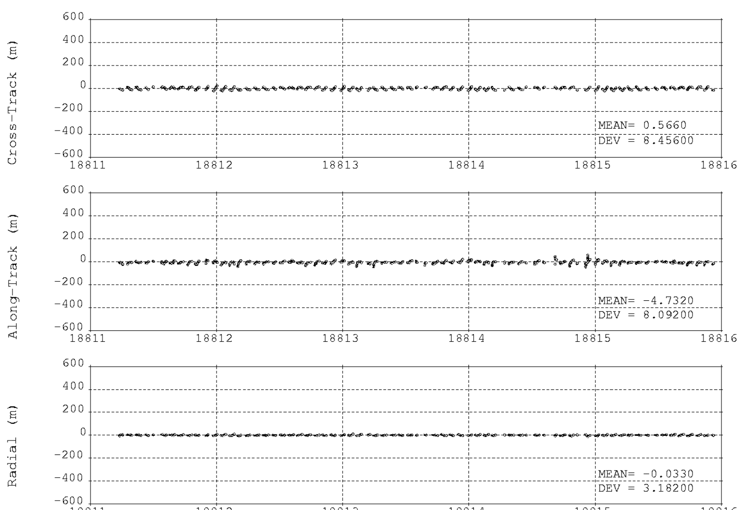


Fig. 7b - DIOGENE ground results with on-board filter parameters

The DIOGENE flight results (Figure 7a) clearly show a high level of error after each data gap. This is due to the method used to increase the clock covariance after the stand-by mode periods (a more efficient method has since been developed, but it cannot be uploaded to HETE-2). In order to obtain the true performance of DIOGENE it would be necessary to operate the receiver without interruption. While this is under discussion with the MIT, an experiment has been conducted on the ground using the measurements received form the spacecraft. Figure 7b shows the results of this processing: the RMS errors are below 20 m on the three axes.

Results can further be improved by tuning the filter parameters (and in particular the ration between the model and measurement covariances). Figure 8 displays the best results that have been obtained over the July 2001 5-day arc used for the computation of the reference orbit (here again assuming continuous operation, that is without stand-by periods).



	mean	std. dev.
Radial (m)	0.0	3.2
Along-track (m)	-4.7	8.1
Cross-track (m)	0.6	8.5

Fig. 9 – performance of DIOGENE on the ground with optimally tuned filter parameters

These results show an along-track bias which is thought to be the result of the same ionosphere effect as seen on the LSIR solution (the equivalent upward radial pull of the ionosphere) filtered by DIOGENE.

During the last year, a complete redesign of DIOGENE has been taking place, to use as its core the BOLERO flight qualified space dynamics library. This new version (version 2.0) also includes new features:

- drag, the effect of Earth orientation (polar motion) and empirical once per revolution accelerations are added to the force models,
- the processing of the GPS phase is added,
- polar motion, empirical parameters and phase ambiguities can be adjusted in the state vector,
- measurements coming from ground pseudolites can be processed, eventually in a simultaneous solution with standard GPS measurements

When this new version of DIOGENE is used to process the HETE-2 data, the results are further improved. In particular, when the phase and pseudo-range data are combined to compensate for the ionosphere the along-track bias disappears, as can be seen in Table 1. The intrinsic performance of the filter was evaluated by processing the same ground ionosphere corrected pseudo-ranges as were used for the reference orbit (column 3). The difference between DIOGENE and the reference orbit is at the same level as the orbit error itself. In all cases, the GPS orbits and clocks used with DIOGENE are the broadcast values, while those used for the reference orbit are the IGS values. This difference does not seem to have a major influence on the solution at the current level of precision.

Table 1 – Performance of DIOGENE V2.0 on HETE-2 data

	Pseudo-range		Pseudo-range + phase		Ionosphere corrected pseudo-ranges	
	mean	std. dev.	mean	std. dev.	mean	std. dev.
Radial (m)	-0.6	2.8	-0.8	4.8	0.5	1.9
Along-track (m)	-5.7	8.2	-0.1	6.8	-0.3	3.9
Cross-track (m)	-1.5	2.9	-0.2	2.7	0.3	1.4

CONCLUSIONS

When the decision to fly a GPS receiver on HETE was taken back in 1992 no one anticipated the level of complexity that this simple experiment would reach in the long term. However, this experiment has also has taught us a few useful lessons

- The TOPSTAR 300 receiver performs according to specifications, with an estimated pseudo-range noise level of about 2.5 m RMS consistent with the observed signal to noise ratio
- In the absence of dual frequency data, the combination of pseudo-range and phase is an efficient method to remove most of the ionosphere delay. The processing of the resulting ambiguous pseudo-range like data type is, however, somewhat difficult. It leads to orbits with a precision of a few meters.
- The DIOGENE software performs well, except for a limitation due to the improper handling of the transitions between stand-by and operational modes. Tests conducted on the ground show that without this limitation, and with a proper tuning of the filter parameters, a 3D precision of 12 meters 1 sigma can be reached

- The new improved DIOGENE version 2.0 software performs even better, as shown in Figure 10

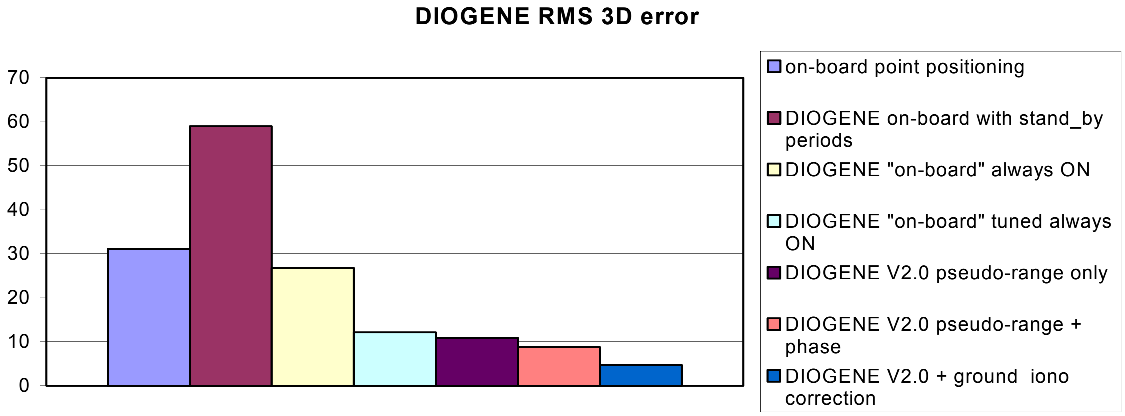


Fig. 10 – Performance of the various DIOGENE configurations

- The operation of a GPS receiver on a microsatellite platform, with the power and telemetry limitations typical of these platforms, is very well suited for operational purposes, but is not a proper way to perform an evaluation of the performance of a receiver and of its on-board orbit determination functions
- A Sun facing GPS antenna on a Sun pointed satellite at low altitude is a good way to run into significant problems with the ionosphere …

The next flight of the TOPSTAR 3000 receiver and of DIOGENE will be on the French experimental telecommunication satellite STENTOR. The receiver will operate both during the transfer to geostationary orbit, and later on, in routine mode in geostationary orbit. Due to the very marginal visibilities accessible from this orbit, the conditions of operation will be at least as difficult as those encountered on HETE- 2!

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